CHAPTER 17

PLATE TECTONICS

MATERIALS NEEDED

- Pencil and eraser
- Metric ruler
- Protractor
- Calculator

INTRODUCTION

The plate tectonic theory is one of the most important and far-reaching theories in geology. It evolved from detailed observations made over many years and from individual hypotheses that required extensive and imaginative testing. For example, measurement of magnetism of the rocks on the seafloor was used as a test for seafloor spreading; the nature and distribution of earthquakes and volcanoes provided a test for plate convergence; and a variety of geological and geophysical studies proved the existence of transform faults. In this lab, a few predictions based on the plate tectonic hypothesis will be tested by analyzing appropriate data.

The theory of plate tectonics was more than 100 years in the making. Beginning in the 19th century, geologists began to compile basic observations about the Earth that could not be explained satisfactorily.

For example:

> Fossils of the same kinds of land-dwelling plants and animals were found on opposite sides of oceans; how did these land dwellers cross the ocean?
>
> Fossils of warm-weather plants and animals were found where climates are now cold, and evidence of glaciation was found in areas that now are warm; were Earth climates radically different in the past?
>
> Earthquakes, volcanoes, and mountains are not randomly distributed about the Earth; why not?

Some interesting hypotheses were developed to explain these observations. To explain the distribution of fossils of land dwellers, it was supposed that continents were connected by land bridges that have since sunk into the oceans. To explain the rock-borne evidence of diverse climates, it was supposed that climates fluctuated widely in the geologic past. To explain the causes and distribution of earthquakes, volcanoes, and mountains, hypotheses involving contraction or expansion of the Earth were proposed; contraction would cause fold-and-thrust-faulted mountains, and expansion would cause fault-block mountains and provide conduits to the surface for magma. None of these hypotheses withstood testing, however, and eventually all were discarded.

The first detailed attempt at a unifying theory, one that could explain most of the major observations, was the continental-drift hypothesis of Alfred Wegener, proposed in a series of papers and books between 1910 and 1928. Wegener's hypothesis was severely criticized, especially by geologists in the northern hemisphere, on the grounds that it was mechanically impossible.

But more and more evidence seemed to suggest that continents indeed had moved relative to one another. Research that began in the late 1920s, and developed through the thirties and forties, indicated that a mechanism involving convection currents within the solid Earth might be possible. Additional geophysical evidence was especially persuasive, and by the early to mid-1960s, the framework of plate tectonics was in place.

At that time, plate tectonics was still a hypothesis, and there were many doubters, ready with observations that could not be readily explained by the existing model. The mark of a good hypothesis is that it can be tested, and the plate tectonics hypothesis offered many tests. Tests are conceived from predictions. That is, if the hypothesis is correct, then we can predict and test for certain consequent relations or results. In this lab, a series of predictions will be evaluated using real data.

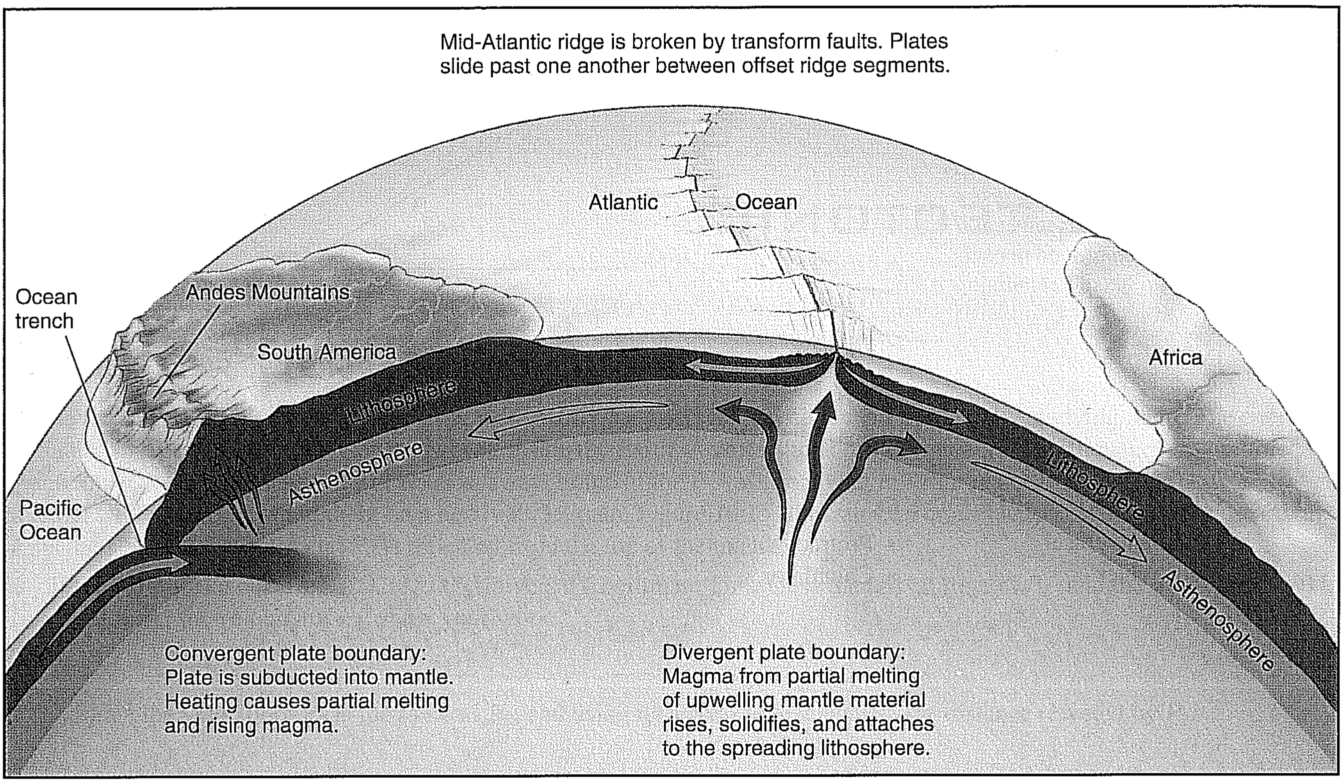


FIGURE 17.1
Cutaway view of the Earth, illustrating plates of lithosphere and the three types of plate boundaries. The thickness of lithosphere and asthenosphere is exaggerated.
Source: Data from USGS, *Professional Paper 1350.*

GENERAL THEORY OF PLATE TECTONICS

According to the theory of plate tectonics, the outermost part of the Earth is made of **lithospheric plates,** some 70 to 125 km thick, that move relative to one another (Fig. 17.1). Plates are constructed by successive injections of magma at **divergent plate boundaries.** The plates move away from the divergent boundaries and, at **convergent plate boundaries,** they encounter other plates moving toward them in a relative sense. There, one of the plates moves beneath the other, and either descends into the mantle or becomes sutured (attached) to the overlying plate. A **transform-fault plate boundary** is a type of strike-slip fault; plates slide past one another, and lithosphere is neither created nor destroyed. Let's look at these three types of plate boundaries in a little more detail.

DIVERGENT BOUNDARIES

Plates move apart at divergent plate boundaries as magma from the mantle wells up to fill the gap between adjacent plates, as shown in Figure 17.2. Divergent boundaries in the oceans are expressed by ridges and rises, generally with a narrow rift valley marking the boundary between plates along a central ridge crest.

Perhaps the most critical piece of evidence for the plate tectonic hypothesis, or at least for the seafloor-spreading component, came in the early 1960s from the study of the magnetic properties of rocks on the floor of the North Atlantic Ocean. This story has two parts.

The first has to do with the way in which an igneous rock retains a record (its **remnant magnetism**) of the existing magnetic field as it cools from a molten state. Recall that some minerals, especially magnetite (Fe_3O_4), are strongly magnetic. However, if they are heated above a certain temperature, the **Curie point** (about 580°C for magnetite), the magnetism disappears. Conversely, magnetite, which forms at about 1100°C as magma crystallizes, becomes magnetic when the temperature drops below its Curie point. Its magnetism aligns with the existing magnetic field, as shown in Figure 17.3A, and is frozen into the rock as though the rock contained tiny bar magnets. Thus, the rock contains a record of the magnetic lines of force at that time and place; the north-seeking ends of the "magnets" point toward magnetic north, and the axes of their magnetic fields are parallel to the **inclination** of the magnetic lines of force. The angle of inclination is determined by the magnetic latitude at which the rock formed (Fig. 17.3A).

The second part of the story has to do with reversals of the magnetic field and **magnetic anomalies** (magnetic values greater or less than expected). In the present-day magnetic field, the north-seeking pole of a magnet points toward the north magnetic pole, which coincides

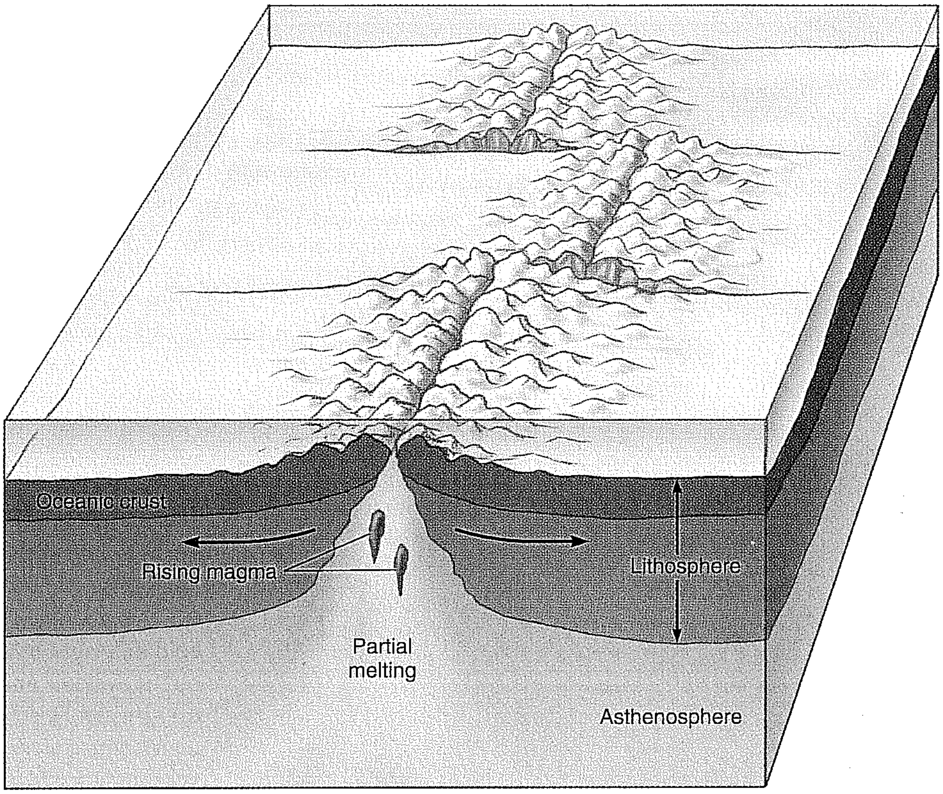


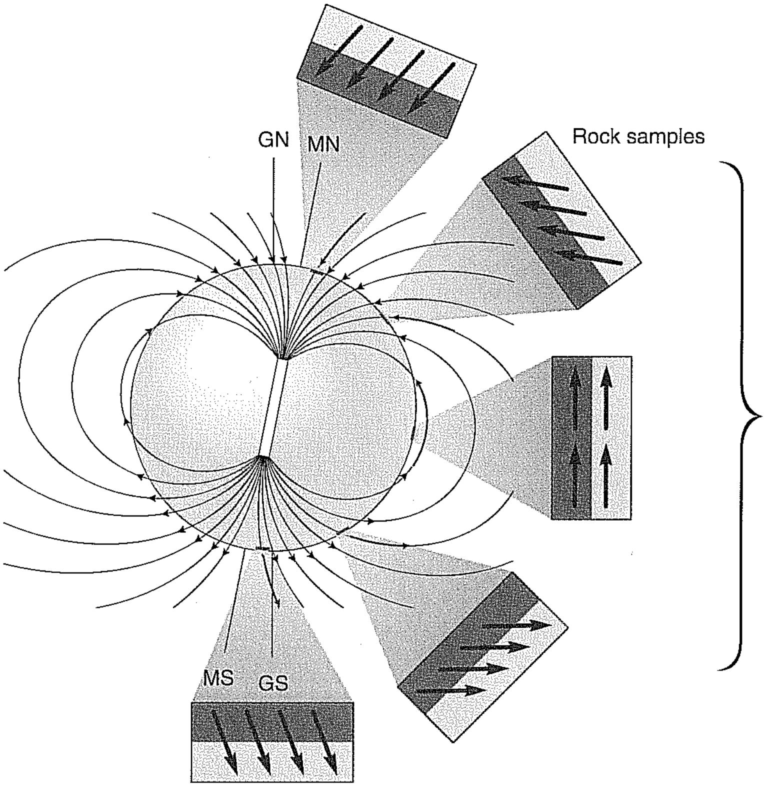
FIGURE 17.2
Block diagram of a mid-ocean ridge, a divergent plate boundary, at which seafloor spreading occurs.

approximately with the north geographic pole. But studies of remnant magnetism show that this has not always been the case. At many times in the geologic past, the orientation of the Earth's magnetic field has been reversed, as shown in Figure 17.3B. During these periods, the north-seeking poles of newly forming mineral "magnets" actually pointed toward the south geographic pole.

Imagine what could happen along a divergent boundary as magma rose, solidified, and took on the magnetic orientation existing at that time. During times of **normal magnetic polarity,** north-seeking remnant magnetic poles would point toward present-day north; during times of **reversed magnetic polarity,** north-seeking poles would point toward present-day south. As more magma is injected, the previously formed lithosphere (with one magnetic orientation) would be forced to move away from the plate boundary in both directions. Should the magnetic field reverse its polarity, newly injected magma would form rock that has a reversed polarity. Thus, as was hypothesized in the 1960s, alternating stripes or bands of rock with either normal or reversed remnant magnetism should form parallel to the divergent ocean ridges. Such magnetic stripes can be detected by a ship towing a magnetometer close to the seafloor. When passing close to rocks with normal remnant magnetism, their magnetic intensity is added to the modern magnetic field and a **positive magnetic anomaly** results. When passing over rocks with a reversed remnant magnetism, a weaker **negative magnetic anomaly** results.

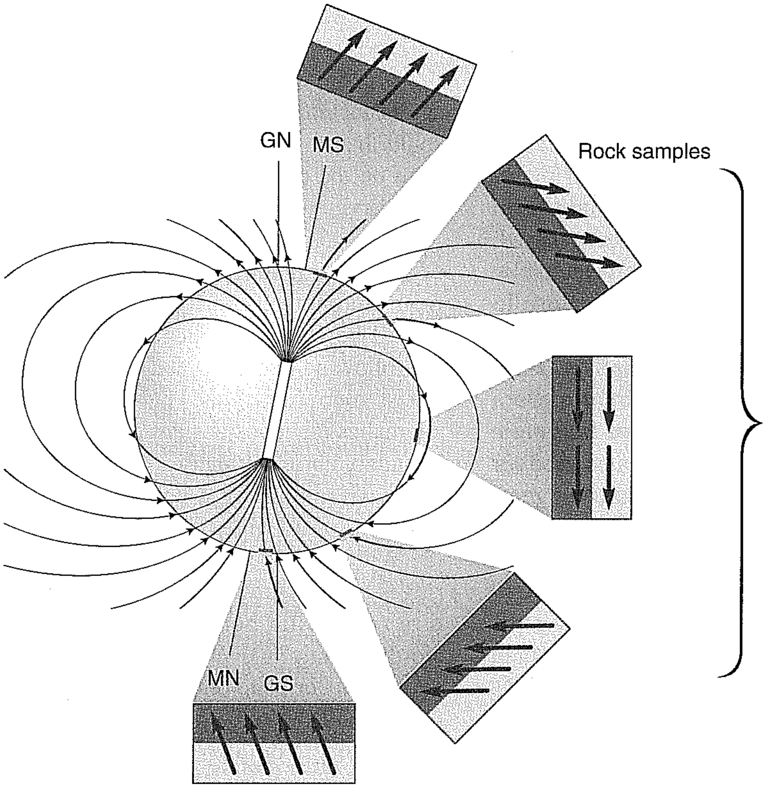
It was an exciting time in geology when parallel bands of positive and negative magnetic anomalies were discovered along the Mid-Atlantic Ridge (Fig. 17.4). Here was a magnetic-tape-like record of past reversals of the magnetic field as recorded by basalt extruded at a divergent plate boundary. If the numerical age of a sample from one of the bands on Figure 17.4 were known (for example, from radioactive isotopes in the sample), then the age of the entire band could be inferred as could that of the symmetrically equivalent band on the opposite side of the divergent boundary.

If seafloor spreading occurs as described, and if magnetic anomalies result from magnetic polarity reversals, you should be able to predict the answers to the following questions and propose ways to test your predictions. (1) Will magnetic anomalies on opposite sides of a divergent boundary correlate; that is, will a negative anomaly indicating a specific reversal occur on both sides of the boundary? (2) Will magnetic data from other ocean ridges or rises show the same general pattern of parallel bands as shown in the North Atlantic? (3) Will specific magnetic anomalies correlate on a worldwide basis; that is, will the same anomalies be found worldwide? You also should be able to propose a way to use the magnetic anomalies to determine the rate at which seafloor spreading has occurred in a given area. Problems 1 and 6 deal with magnetic anomalies at divergent plate boundaries.



Basalt samples from various latitudes have *normal* remnant magnetism. Arrows in samples are parallel to, and point in the same direction as, magnetic lines of force at each location and reflect the magnetic latitude at which rocks formed. Yellow marks upper half of sample.

A. Normal geomagnetic polarity



Basalt samples from various latitudes have *reversed* remnant magnetism. Arrows in samples are parallel to, and point in the same directions as, magnetic lines of force at each location and reflect the magnetic latitude at which rocks formed. Yellow marks upper half of sample.

B. Reversed geomagnetic polarity

CONVERGENT BOUNDARIES

Plates come together at convergent boundaries, as illustrated in Figure 17.5. Converging plates contain either oceanic crust or continental crust at their leading edge. When two plates with oceanic crust converge, one dives, or is **subducted,** below the other (Fig. 17.5A). When an oceanic plate and a continental plate converge, the more dense oceanic plate is subducted beneath the continental plate (Fig. 17.5B). When two continental plates collide, partial subduction is accompanied by intense deformation and eventual suturing of segments of the subducted plate to the base of the overriding plate (Fig. 17.5C).

A subducted plate is comparatively cold and rigid when it begins its descent, but it warms and softens as it moves downward. Let's consider two of the many consequences implied by the converging process.

EARTHQUAKES

Most of the world's major earthquakes take place on convergent plate boundaries. The zone along which most occur is named the **Benioff zone,** after seismologist Hugo Benioff. The faulting that generates the earthquakes is both along the boundary between the two lithospheric plates and within the descending slab itself (Fig. 17.5).

FIGURE 17.3

Earth's magnetic lines of force during (A) *normal* and (B) *reversed* geomagnetic polarity. During normal polarity, the magnetic north pole (MN) is near the geographic north pole (GN). When the magnetic pole is reversed, MN is near the geographic south (GS). Lavas that cooled through the Curie point during normal polarity have a normal remnant magnetism with an orientation appropriate to the latitude at which they formed. This is illustrated in A by the red and yellow rock samples from various latitudes; samples with *reversed remnant magnetism* are shown in B.

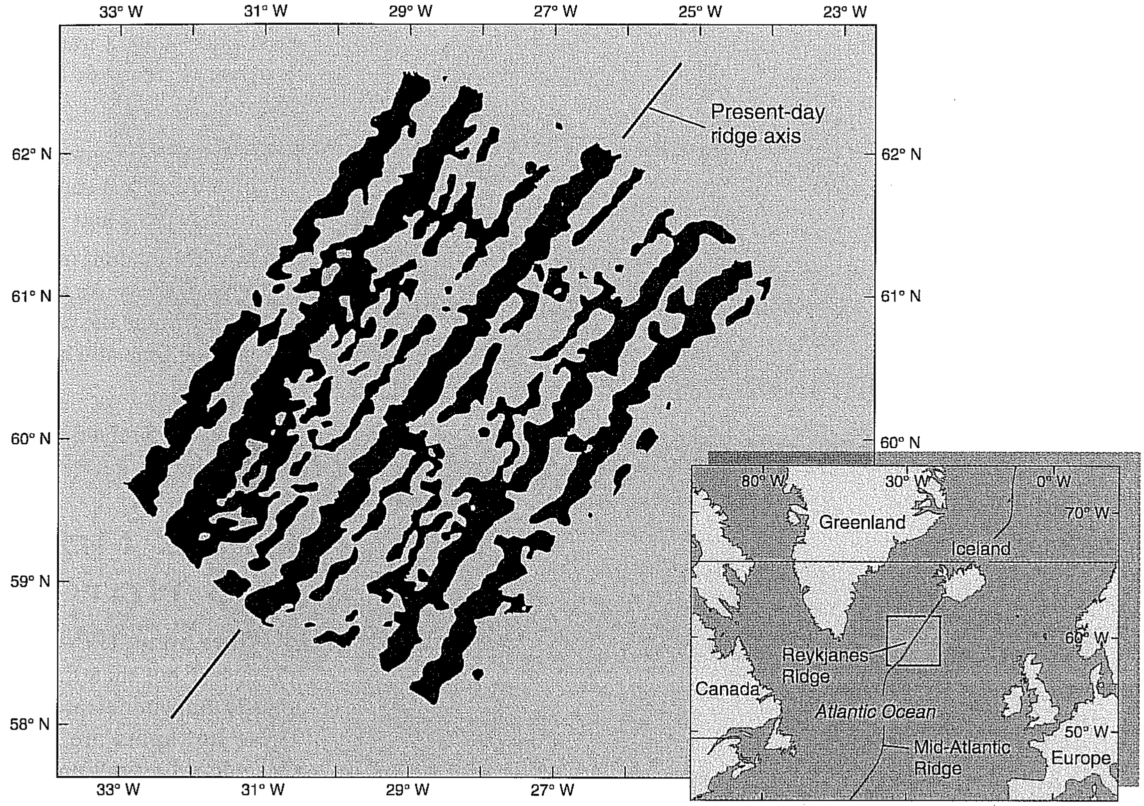


FIGURE 17.4

Symmetrical magnetic anomalies about the Reykjanes Ridge portion of the Mid-Atlantic Ridge, southwest of Iceland. Dark areas are positive magnetic anomalies, light areas between them are negative anomalies. Spreading is perpendicular to the ridge axis.

Source: "Symmetrical magnetic anomalies about the Reykjanes Ridge portion of the Mid-Atlantic Ridge" from "Spreading of the Ocean Floor: New Evidence" by F. J. Vine in *Science,* Figure 2, Vol. 154, 1966, p. 107. Copyright © 1966 American Association for the Advancement of Science. Reprinted with permission.

If convergence does take place as outlined, you should be able to predict the answers to the following questions, and propose ways to test your predictions. (1) Are earthquakes likely to be shallow (0–70 km), intermediate (70–300 km), or deep focus (300–700 km), or will there be a range of focal depths? (2) Will earthquake foci show the angle at which the plate descends? Problem 2 deals with these predictions.

VOLCANIC ARCS

Volcanic, or magmatic, arcs are associated with convergent plate boundaries. The volcanoes usually occur 100 to 300 km away from the trench that marks the position of the subduction zone on the surface, and are located on the same side of the trench as the earthquake epicenters. The implication is that magma is generated as a result of the subduction process.

Given these general observations and the hypothesis of plate tectonics, (1) suggest a process by which magma forms as a result of subduction; (2) predict how the **arc-trench gap** (the horizontal distance between the arc and the trench) may be related to the dip of the Benioff zone; and (3) predict whether subducted lithosphere must reach a certain depth for magma to form. Problem 2 relates to volcanic arcs.

TRANSFORM FAULTS

Transform faults are so called because they transform motion from one plate boundary to another. For example, mid-ocean divergent boundaries are broken into numerous segments by transform faults (Fig. 17.6). Transform faults are strike-slip faults; the principal movement on them is horizontal, and fault planes are essentially vertical. Like strike-slip faults, the sense of movement is described as right-lateral or left-lateral, depending on whether rocks on one side of the fault appear to have moved to the right or left, when viewed from the other side of the fault. Notice that the *apparent* sense of movement on a transform fault may be different than the *actual* sense of movement. For example, in Figure 17.6, the apparent offset of the ridges is right-lateral, but because of the divergence process, the actual movement is left-lateral, as shown by the arrows. Furthermore, movement is taking place only between the two segments of the offset ridge.

As with any other kind of fault, movement along a transform fault results in offset of features on opposite sides. Suggest:

1. how the total amount of movement on a transform can be determined from offsets, and
2. how the amount of offset and the ages of the rocks offset can be used to determine the rate of movement and the time at which movement began.

Problem 5 relates to transform faults.

PLATE MOTION AND HOT SPOTS

At more than 100 places on Earth, plumes of hot material rise through the mantle and penetrate the lithosphere. These **hot spots** are sites of persistent volcanic activity. Some, like Iceland, coincide with present-day divergent boundaries, but many do not. Those hot spots within plates may produce strings of volcanoes that form as lithosphere drifts over them (Fig. 17.7). The volcanoes are active when directly over the hot spot, but die out as the lithosphere drifts on.

The position of these plumes within the mantle is fixed, which makes them useful in testing several aspects of plate-tectonic theory. Predict how the ages of hot-spot-produced volcanoes should vary with distance from the hot spot, and suggest a way to test your prediction. Suggest how hot-spot tracks (strings of volcanoes) could be used to monitor the direction of plate movement through time. Problem 3 relates to hot spots.

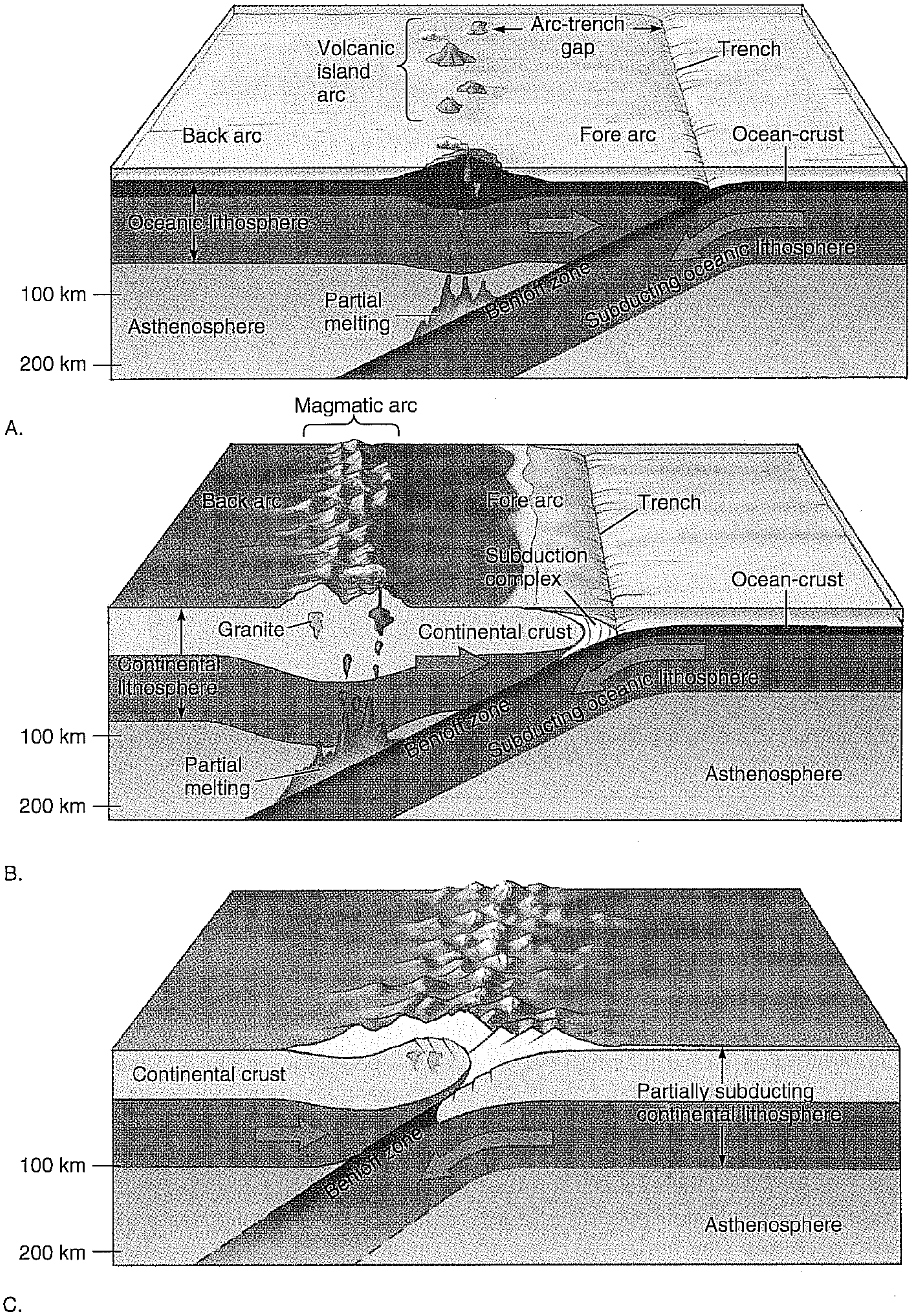


FIGURE 17.5
Block diagrams of convergent plate boundaries. A. Both plates contain oceanic crust.
B. Subducting plate contains oceanic crust; overriding plate contains continental crust.
C. Both plates contain continental crust. The subducted part of the slab in C is oceanic crust subducted before the continents collided.

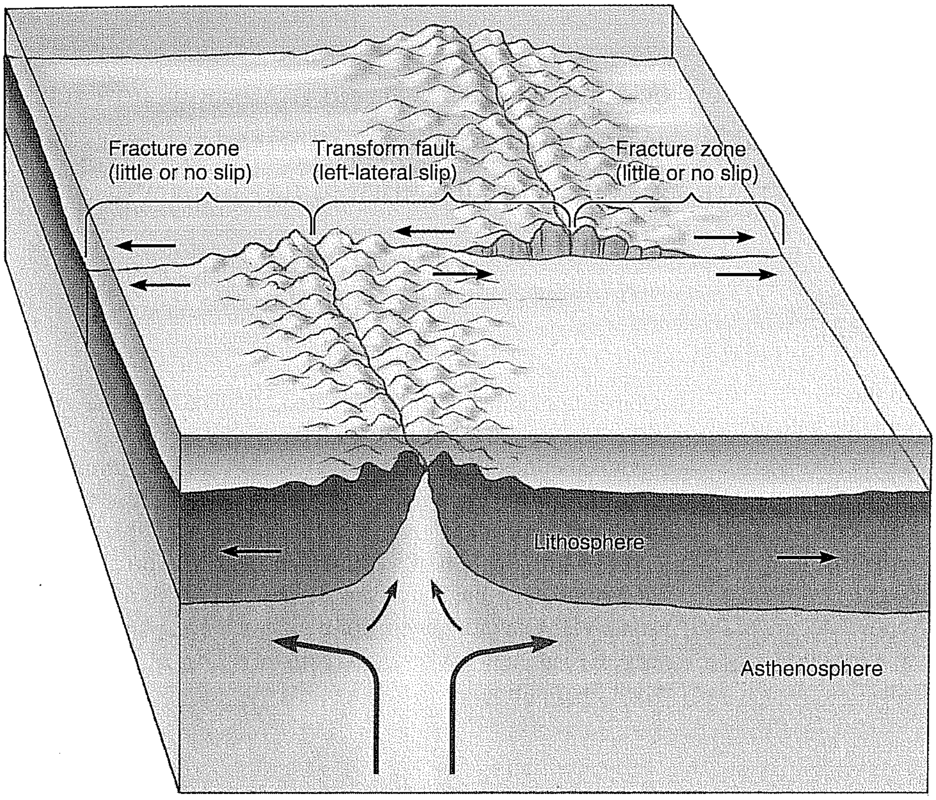


FIGURE 17.6
Transform fault joining segments of a mid-ocean-ridge, divergent-plate boundary. Movement on fault takes place between ridges but not on fracture-zone extensions.

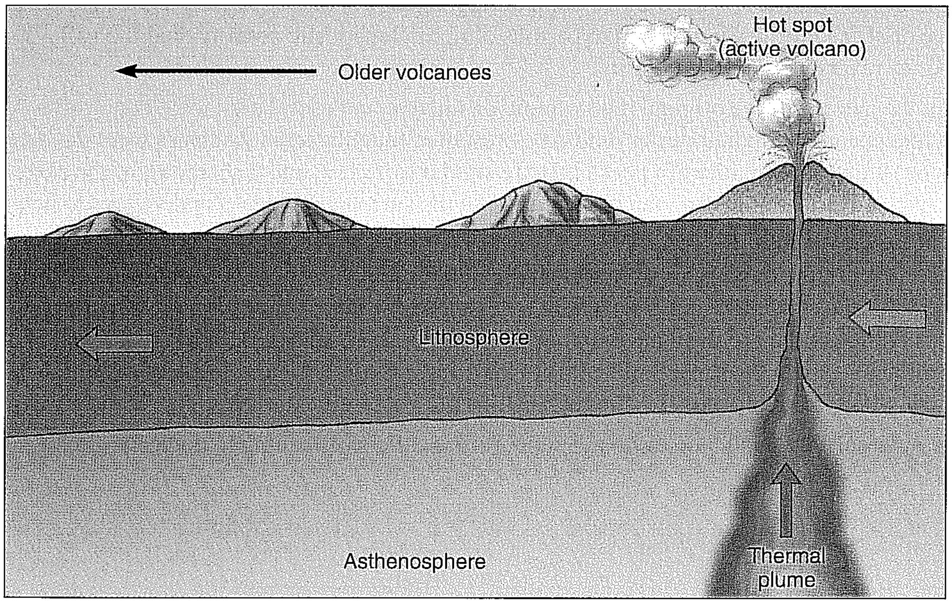


FIGURE 17.7
A fixed heat and magma source below the lithosphere causes a hot spot on the surface. As the lithosphere moves, a string of volcanoes is formed. Older volcanoes are lower and more rounded, because they have undergone more erosion.